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THE STRUCTURE OF TURBULENT VELOCITY FIELDS.(U)
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An experimental investigation of relaminarization of turbulent pipe flow subjected to a large decrease in Reynolds number was continued. A considerable amount of data on the downstream development of the flow field using both single wires and x-wires was obtained. For Re < 2000 the turbulence cannot sustain itself and the flow relaminarizes with the rate of relaminarization being greater the lower the Reynolds number. The mean velocity profiles exhibit a gradual trend towards a parabolic profile with

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20. Abstract

increasing x/d. The nature of the flow field for $1900 < Re < 2800$ was shown to be particularly interesting as puffs or incipient puffs exist in the flow for $x/d > 40$. Detection of puffs imbedded in the decaying turbulent flow is difficult so an iterative puff waveform eduction program was developed. Local detection criteria are used to select puff like events from the velocity signal. Then a global criterion of the puff waveform is generated by using the ensemble averaged eduction waveform as a pattern and then cross-correlating this pattern with each individual event. Based on criteria regarding the maximum cross-correlation and its time delay for any given event, some events are discarded and a new ensemble average is formed, and so on. The process seems to "converge" reasonably rapidly. Valuable results from the program include the average incipient waveform in an incipient puff, the average length of puffs, the mean time puffs, and other structural features of the puffs at various downstream locations. This information is useful in understanding the origin and evolution of puffs in transitional pipe flow. The existence of puffs in the present study as well as a previous transition study indicates that they play a fundamental role in the transition and reverse transition process.

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FINAL SCIENTIFIC REPORT FOR GRANT AFOSR 77-3172

The Structure of Turbulent Velocity Fields

F. H. Champagne

Review of Results

1. Relaminarization of Turbulent Pipe Flow

The experimental investigation of relaminarization of turbulent pipe flow subjected to a large decrease in Reynolds number was continued. The Reynolds number of the flow is decreased a factor of 5 by expanding the initially fully developed turbulent flow through a 1^{o} half angle diffuser. Turbulent pipe flow cannot sustain itself below some critical value of Reynolds number and the reason for this is not yet known. As the initial state of the flow is turbulent, no analytical approach to this problem is yet feasible and the goal of the present experimental study is to understand the basic mechanism of the relaminarization process. Such knowledge is highly desirable if one hopes to control transition to and from turbulence.

The flow facility consists of a flow source, a 0.10 inch orifice plate, a cylindrical pipe 0.20 inches in i.d. and 120 diameters long to establish a fully developed initial pipe flow, then the 1^{o} half angle diffuser section. The flow passes from the diffuser into a constant area downstream pipe, the length of which can be varied to allow investigation of the flow at various stages of the relaminarizing process. The objectives of the study are to: (1) investigate the nature of the relaminarization process by measuring the development or decay rate of the turbulent velocity field; (2) establish the minimum downstream Reynolds number for which the flow remains fully turbulent through the diffuser and downstream pipe; (3) examine flow fields in the range $1900 < Re < 3000$ (downstream Reynolds number) for the existence of puffs which appear to form even in the presence of the high intensity decaying ambient turbulence. A considerable amount of data has now been obtained and brief discussion of some aspects of the results will be presented.

Data on the downstream development of the mean velocity and turbulence intensity profiles in the constant area pipe has been obtained for various Reynolds numbers. The Reynolds numbers are based on the flow conditions in the downstream pipe and the velocity scale used is the bulk velocity. The latter is the cross-sectional averaged mean velocity. Some of this data was obtained under Grant 72-2287. The more recent data, which represents a significant portion of the total data, was taken after analysis and consideration of the preliminary data. There are some interesting features regarding the development of the mean velocity profiles for the Reynolds number range between 2000 and 3000, but this will not be discussed here. For $Re < 2000$, the profiles exhibit a gradual change towards a parabolic profile with increasing x/d. The initial turbulence levels at the diffuser exit plane (for all cases) are considerably greater than that occurring in fully developed pipe flow. The turbulence intensity decreases with increasing downstream distance for all the

$Re < 2000$ cases with the rate of relaminarization being greater the lower the Reynolds number.

The $2000 < Re < 2800$ range is especially interesting as the turbulence intensity appears to be increasing with downstream distance beyond $x/d \sim 30$, where it is already greater than the fully developed pipe flow values. Evidence for the existence of puffs or incipient puffs is present in the data and these intermittently occurring events are the cause of the high intensity values. This type of behavior ceases for $Re > 2800$ where no puffs appear and the flow stays fully turbulent throughout the pipe. The incipient puffs imbedded in the decaying ambient turbulence are difficult to detect, but are definitely in the flow even though it is already turbulent. This is of fundamental interest as it indicates that puffs are characteristic of transitional pipe flow for a given Reynolds number regardless of the nature or exact level of the disturbances present in the flow providing some threshold level is exceeded.

Detection of the puffs or incipient puffs is difficult for at least two reasons. One is that the puff velocity waveform has no definite leading and trailing edges that can be used to define a time reference point. Time reference points are useful for aligning waveforms for ensemble averaging. The other main problem is to distinguish puff waveform signatures from those of the ambient turbulence. To circumvent these problems, it was decided to utilize a technique similar to the iterative pattern recognition scheme developed by Wygnanski and Kaplan to study transitional spots in a boundary layer. A puff waveform eduction program was developed and the data acquisition and eduction scheme are essentially as follows. The velocity signals are digitized, typically with a sampling frequency of 2000 Hz, and placed on a digital tape for analysis. The digitized time series are read onto the 7600 computer where the data is stored and a second channel is generated by low pass filtering the data at 20 Hz using a zero phase shift digital filter. The filtered velocity data is searched for velocity minima which fell below some prescribed threshold value. This criterion, the local detection criterion, is based on the established existence of a velocity minimum on the pipe centerline near the trailing edge of a fully developed puff. Tests on the relative locations of adjacent minima are performed to eliminate minima which are too closely spaced to allow a puff between them. The time locations of the minima and of the leading and trailing "edges" associated with the minima are stored. Also stored are 1000 time series points before and 600 after the location of each minimum. These 1600 point sets define the filtered puff or realization. Similarily, 1600 points for the unfiltered signal are stored and define the unfiltered event. Typically, 100 event pairs are detected and stored except at the low Reynolds number case, Re = 1928, where only 10 events occurred in 20 minutes of data. The unfiltered and filtered events are respectively ensemble averaged. The averaged unfiltered event, or ensemble averaged educted waveform, forms the "global criterion" of a puff waveform.

The "zeroeth" iteration is defined as the first ensemble average of the unfiltered events. This zeroeth iteration is then cross-correlated with each individual filtered event to obtain a time delay of maximum correlation, τ_M, and the value of the maximum correlation coefficient, c_M. Histograms of τ_M and c_M are formed and then criteria on the minimum value of c_M and the time delay range about τ_M to be accepted are applied to eliminate some events from consideration. A new table of acceptable events is formed, events are shifted in time to improve alignment, and the new ensemble averages are formed. The new unfiltered average is termed the "first" iteration. This process is repeated again and so on until convergence is obtained. Preliminary studies indicate three to four iterations are sufficient to converge in some sense using reasonable criteria on τ_M and c_M. Further work to quantify convergence is underway. Some results for the average length of puffs, the mean time between puffs, and other structural features of the puffs or incipient puffs or have been obtained for various downstream positions and for several Reynolds numbers.

A similar puff waveform eduction scheme is being tested using velocity signals obtained near the wall. In a puff a velocity maximum is attained near the trailing edge, so the local detection criterion is changed to search for maxima with the remainder of the program remaining unchanged. The puff waveform eduction scheme has been applied to x-wire data to determine the turbulent shear stress during a puff or incipient puff event. The results are still of a preliminary nature and shall not be reported on. Refinement of various aspects of the puff waveform eduction program are still underway. Current efforts are centered on studying the origin and evolution of puffs in transitional pipe flow.

Finally, it should be noted that at a Reynolds number of approximately 2800, a complete and definite disappearance of puff like behavior in the velocity signal occurs. The hot wire traces appear more characteristic of those of fully developed pipe flow or homogeneous turbulence in contrast to the $2000 < Re < 2800$ range traces.

2. The Temperature Sensitivity of Hot Wires

The investigation of the temperature sensitivity of hot wires at high overheat ratios was completed. The results of the work were presented at an invited lecture in the 1978 Dynamic Flow Conference held at Johns Hopkins University. A manuscript based on the results of the investigation was prepared and accepted for publication in the conference proceedings. An abstract of the publication is included on the following page.

THE TEMPERATURE SENSITIVITY OF HOT WIRES

by

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ABSTRACT

Significant errors in measurements of some velocity and joint velocity-temperature statistics arise from the non-negligible contamination of the measured hot-wire velocity signal by concomitant temperature fluctuations. Measurements of the temperature sensitivity of hot wires operated at high overheat ratios are considerably more difficult to obtain than measurements of the velocity sensitivity. Therefore to provide a check on the measured values, an analytical expression for the temperature sensitivity is derived which can be evaluated from parameters readily obtained from the velocity calibration data. The analysis, based on the convective heat transfer relation of Collis and Williams (1959), gives values of the temperature sensitivity which compare well with directly measured values. The present analysis is extended to show that the temperature and velocity sensitivities can be expressed entirely in terms of the linearized voltage output obtained by direct calibration for each hot-wire or hot-film sensor. Estimates of the errors in some measured statistics caused by the concomitant temperature fluctuation contamination of the hot-wire signal are determined.

Publications During Grant Period

1. Champagne, F. H., "The Fine Scale Structure of Turbulent Velocity Fields", J. Fluid Mech. 86, pp. 67-108, 1978.

2. Champagne, F. H., "The Temperature Sensitivity of Hot Wires", accepted for publication in the 1978 Dynamic Flow Conference Proceedings.

Abstracts and Presentations During Grant Period

1. Champagne, F. H. and K. Helland, "Pipe Flow Relaminarization", presented at 1978 Amer. Phys. Soc. Fluid Dynamics Meeting at the University of Southern California, Los Angeles, Calif., November 19-21, 1978. Bull. Amer. Phys. Soc., Series II, 23 (11), 1978.

2. Champagne, F. H. "The Fine Scale Structure of Turbulent Velocity Fields", lecture presented at the University of Arizona, Tucson, Arizona, April 20, 1978.

3. Champagne, F. H., "Hot-Wire and Hot-Films as Velocity and Temperature Sensors", "Signal Processing", and "Measuring Turbulence in the Atmosphere and Ocean", invited lectures presented in a Short Course on Dynamic Flow Measurement Techniques at the State University of New York at Buffalo, Buffalo, N. Y., August 2-4, 1978.

4. Champagne, F. H., "The Temperature Sensitivity of Hot Wires", invited lecture presented at the 1978 Dynamic Flow Conference held at the Johns Hopkins University, Baltimore, Maryland, September 18-21, 1978.